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Universal Lepton Asymmetry: New Constraints from the Cosmic Microwave Background and Primordial Nucleosynthesis

T. KAJINO, M. ORITO

National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan;
E-mail: kajino@nao.ac.jp

and

G. J. MATHEWS

Department of Physics and Center for Astrophysics, University of Notre Dame, Notre Dame, IN 46556, U.S.A.

and

R. N. BOYD

Department of Physics and Department of Astronomy, Ohio State University, Columbus, OH 43210, U.S.A.

Abstract

We study the primordial nucleosynthesis and cosmic age in the presence of a net lepton asymmetry as well as baryon asymmetry. We explore a previously unnoted region of the parameter space in which very large baryon densities $0.1 \leq \Omega_b \leq 1$ can be accommodated within the light-element constraints from primordial nucleosynthesis. This parameter space consists of ν_μ and ν_τ degeneracies with a small ν_e degeneracy. Constraints from cosmic microwave background fluctuations are also discussed [1].

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1 Introduction

Recent progress in cosmological deep survey has clarified progressively the origin and distribution of matter and evolution of Galaxies in the Universe. The origin of the light elements among them has been a topic of broad interest for its significance in constraining the dark matter component in the Universe and also in seeking for the cosmological model which best fits the recent data of cosmic microwave background (CMB) fluctuations. This paper is concerned with neutrinos during Big-Bang nucleosynthesis (BBN). In particular, we consider new insights into the possible role which degenerate neutrinos may have played in the early Universe. There have been many important contributions toward constrainig neutrino physics. Hence, a discussion of neutrinos and BBN is even essential in particle physics as well as cosmology.

There is no observational reason to insist that the universal lepton number is zero. It is possible, for example, for the individual lepton numbers to be large compared to the baryon number of the Universe, while the net total lepton number is small $L \sim B$. It has been proposed recently [2] that models based upon the Affleck-Dine scenario of baryogenesis might generate naturally lepton number asymmetry which is seven to ten orders of magnitude larger than the baryon number asymmetry. Neutrinos with large lepton asymmetry and masses $\sim$ 0.07 eV might even explain the existence of cosmic rays with energies in excess of the Greisen-Zatsepin-Kuzmin cutoff [3]. It is, therefore, important for both particle physics and cosmology to carefully scrutinize the limits which cosmology places on the allowed range of both the lepton and baryon asymmetries.

2 Primordial Nucleosynthesis

CMB power spectrum is expected to provide a precise value of the universal baryon-mass density parameter Ω_b along with the other cosmological parameters. It is therefore a critical test if the Big-Bang nucleosynthesis can predict a consistent Ω_b-value.

There is a potential difficulty in the determination of Ω_b from primordial nucleosynthesis, which has been imposed by recent detections of a low deuterium abundance, $2.9\times10^{-5} \leq \mathrm{D/H} \leq 4.0\times10^{-5}$, in Lyman-$\alpha$ clouds along the line of sight to high red-shift quasars [4]. Primordial abundance of ^{7}Li is constrained from the observed "Spite plateau", $0.91\times10^{-10} \leq {}^7\mathrm{Li/H} \leq 1.91\times10^{-10}$ [5], and the ^{4}He abundance by mass, $0.226 \leq Y_p \leq 0.247$ [6], from the observations in the HII regions. In order to satisfy these abundance constraints by a single Ω_b value, one has to assume an appreciable depletion in the observed abundance of ^{7}Li, which is still controversial both theoretically and observationally.

It depends on how accurately the nuclear reaction rates for the production of ^{7}Li are known. ^{7}Li abundance is strongly subject to large error bars associated with the measured cross sections for $^4\mathrm{He}(^3\mathrm{H},\gamma)^7\mathrm{Li}$ at $\eta \lesssim 2\times10^{-10}$ and $^4\mathrm{He}(^3\mathrm{He},\gamma)^7\mathrm{Be}$ at $3\times10^{-10} \lesssim \eta$. We studied these two reactions in quantum mechanics very carefully and concluded that the proper 2σ error bars could be 1/4$\sim$1/3 of the previous ones. This improvement owes

mostly to, first, the new precise measurement [7] of the cross sections for ^{4}He(^{3}H,γ)^{7}Li and, second, the systematic theoretical studies [8] of both reaction dynamics and quantum nuclear structures of ^{7}Li and ^{7}Be, whose validity is critically tested by electromagnetic form factors measured by high-energy electron scattering experiments. When our recommended error estimate is applied to the determination of Ω_b, we lose Ω_b value to explain both D/H and ^{7}Li/H simultaneously.

In order to better estimate the Ω_b-value, we propose a new method to determine the primordial ^{7}Li by the use of isotopic abundance ratio ^{7}Li/^{6}Li in the interstellar medium which exhibits the minimum effects of the stellar processes including depletion effect. Details are reported elsewhere [9, 10].

3 Neutrino Decoupling in Lepton Asymmetric Cosmology

Although lepton asymmetric BBN has been studied in many papers [11] (and references therein), there are several differences in the present work: For one , we have included finite temperature corrections to the mass of the electron and photon [12]. Another is that we have calculated the neutrino annihilation rate in the cosmic comoving frame, in which the Møller velocity instead of the relative velocity is to be used for the integration of the collision term in the Boltzmann equations [13, 14].

Neutrinos and anti-neutrinos drop out of thermal equilibrium with the background thermal plasma when the weak reaction rate becomes slower than the universal expansion rate. If the neutrinos decouple early, they are not heated as the particle degrees of freedom change. Hence, the ratio of the neutrino to photon temperatures, T_ν/T_γ, is reduced. The biggest drop in temperature occurs for a neutrino degeneracy parameter $\xi_\nu = \mu_\nu/T_\nu \sim 10$, where μ_ν is the neutrino chemical potential. This corresponds to a decoupling temperature above the cosmic QCD phase transition.

Non-zero lepton numbers affect nucleosynthesis in two ways. First, neutrino degeneracy increases the expansion rate. This increases the ^{4}He production. Secondly, the equilibrium n/p ratio is affected by the electron neutrino chemical potential, n/p = $\exp\{-(\Delta M/T_{n\leftrightarrow p}) - \xi_{\nu_e}\}$, where ΔM is the neutron-proton mass difference and $T_{n\leftrightarrow p}$ is the freeze-out temperature for the relevant weak reactions. This effect either increases or decreases ^{4}He production, depending upon the sign of ξ_{ν_e}.

A third effect emphasized in this paper is that T_ν/T_γ can be reduced if the neutrinos decouple early. This lower temperature reduces the energy density of neutrinos during BBN, and slows the expansion of the Universe. This decreases ^{4}He production.

Figure 1 highlights the main result of this study [1], where we take $\xi_{\nu_\mu} = -\,\xi_{\nu_\tau}$. For low $\Omega_{\rm b}h_{50}^2$ models, only the usual low values for ξ_{ν_e} and $\xi_{\nu_{\mu,\tau}}$ are allowed. Between $\Omega_{\rm b}h_{50}^2 \approx$ 0.188 and 0.3, however, more than one allowed region emerges. For $\Omega_{\rm b}h_{50}^2 \gtrsim 0.4$ only the large degeneracy solution is allowed. Neutrino degeneracy can even allow baryonic

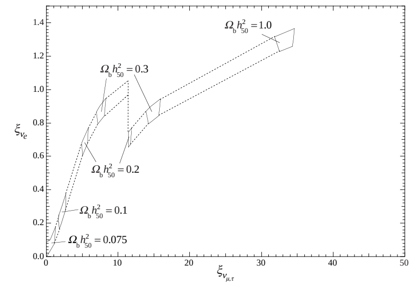

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Figure 1: Allowed values of ξ_{ν_e} and $\xi_{\nu_{\mu,\tau}}$ for which the constraints from light element abundances are satisfied for values of $\Omega_{\rm b}h_{50}^2 = 0.075$, 0.1, 0.2, 0.3 and 1.0 as indicated.

densities up to $\Omega_{\rm b}h_{50}^2 = 1$.

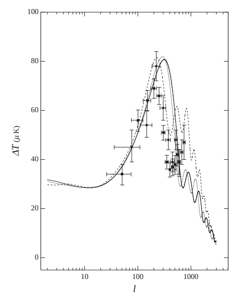

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Figure 2: CMB power spectrum from MAXIMA-1 [19] (circles) and BOOMERANG [18] (squares) binned data compared with calculated $\Omega = 1$ models.

4 Constraint from Cosmic Microwave Background

Several recent works [15, 16, 17] have shown that neutrino degeneracy can dramatically alter the power spectrum of the CMB. However, only small degeneracy parameters with the standard relic neutrino temperatures have been utilized. Here, we have calculated the CMB power spectrum to investigate effects

of a diminished relic neutrino temperature.

The solid line on Figure 2 shows a $\Omega_\Lambda = 0.4$ model for $n = 0.78$ which is a power law "tilt" of primordial fluctuation. This fit is marginally consistent with the data at a level of 5.2σ. The dotted line in Figure 2 shows the matter dominated $\Omega_\Lambda = 0$ best fit model with $n = 0.83$ which is consistent with the data at the level of 3σ. The main differences in the fits between the large degeneracy models and our adopted benchmark model are that the first peak is shifted to slightly higher l value and the second peak is suppressed. One can clearly see that the suppression of the second acoustic peak is consistent with our derived neutrino-degenerate models. In particular, the MAXIMA-1 results are in

very good agreement with the predictions of our neutrino-degenerate cosmological models [1, 20]. It is clear that these new data sets substantially improve the goodness of fit for the neutrino-degenerate models [16]. Moreover, both data sets seem to require an increase in the baryonic contribution to the closure density as allowed in our neutrino-degenerate models.

5 Cosmic Age

There are several important implications of the neutrino degenerate Universe models. One of them is on the cosmic age problem. Recent baloon experiments of detecting the CMB anisotropy has exhibited that the flat cosmology is more likely. Combining this with the result from high-redshift supernova search, one may deduce a finite cosmological constant $\Omega_\Lambda \sim 0.6$, leading to a cosmic age ~ 15 Gy. If this were the case, a potential difficulty that the cosmic age is likely to be shorter than the age of the Milky Way might be resolved. However, CMB anisotropy data provide with more details of sesveral cosmological parameters which may not necessarily accept this simplified interpretation.

In our neutrino degenerate Universe models with $\Omega = 1$, $\Omega_\Lambda = 0.4$, and $\Omega_b h_{50}^2 = 0.1$, neutrino mass for $\nu_{\mu,\tau}$ is constrained $m_\nu \leq 0.3$ eV as far as $\Omega_\nu \leq 0.5$ [1, 20]. Even should the mass be 0.3 eV, our conclusion on the primordial nucleosynthesis does not change at all. Therefore, we assumed massless neutrino. With this possible choice of the parameters in cosmology and particle physics, we can estimate the cosmic expansion age $\approx 12 \sim 13$ Gy. Cosmic age problem seems still remained. Further careful studies of the age problem and also the nature of cosmological constant [21] are highly desirable.

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